

Post-Sphaleron baryogenesis and $n - \bar{n}$ oscillation in non-SUSY $SO(10)$ GUT with gauge coupling unification and proton decay

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Abstract

Post-sphaleron baryogenesis”, a fresh and profound mechanism of baryogenesis accounts for the matter-antimatter asymmetry of our present universe in a framework of Pati-Salam symmetry. We attempt here to embed this mechanism in a non-SUSY $SO(10)$ grand unified theory by reviving a novel symmetry breaking chain with Pati-Salam symmetry as an intermediate symmetry breaking step and as well to address post-sphaleron baryogenesis and neutron-antineutron oscillation in a rational manner. The Pati-Salam symmetry based on the gauge group $SU(2)_L \times SU(2)_R \times SU(4)_C$ is realized in our model at $10^5 - 10^6$ GeV and the mixing time for the neutron-antineutron oscillation process having $\Delta B = 2$ is found to be $\tau_{n-\bar{n}} \simeq 10^8 - 10^{10}$ secs with the model parameters which is within the reach of forthcoming experiments. Other novel features of the model includes low scale right-handed W_R^\pm , Z_R gauge bosons, explanation for neutrino oscillation data via gauged inverse (or extended) seesaw mechanism and most importantly TeV scale color sextet scalar particles responsible for observable $n - \bar{n}$ oscillation which can be accessible to LHC. We also look after gauge coupling unification and estimation of proton life-time with and without the addition of color sextet scalars.

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I. INTRODUCTION

The Standard Model (SM) of particle physics has given us enough reasons to look beyond its framework for dealing with issues like tiny neutrino masses, matter-antimatter asymmetry of the present universe, Dark matter and Dark energy, coupling unification of three fundamental interactions. Among all these, the observed baryon asymmetry of the universe has motivated the scientific community to work upon it since a long time. The WMAP satellite data [1, 2], when combined with large scale structures (LSS) data, gives the baryon asymmetry of the universe to be $\eta^{\text{CMB}} \simeq (6.3 \pm 0.3) \times 10^{-10}$ while an independent measurement of baryon asymmetry carried out by BBN [3] yields $\eta^{\text{BBN}} \simeq (3.4 - 6.9) \times 10^{-10}$. Two compelling mechanisms namely Leptogenesis [4] and Weak scale baryogenesis [5] have been prime tools for explaining baryon asymmetry of the universe. In leptogenesis the desired lepton asymmetry is created by the lepton number violating as well as out of equilibrium decays of heavy particles which is subsequently converted into baryon asymmetry by the non-perturbative $(B + L)$ -violating sphaleron interactions [6, 7].

An inadequate knowledge about the nature of new physics beyond the standard model leaves us with no choice but to explore all possibilities which may explain the origin of matter-antimatter asymmetry. Recently a new idea behind baryon asymmetry has been explored named "Post-Sphaleron baryogenesis (PSB)" which occurs via the decay of a scalar boson singlet under standard model having mass around few hundreds of GeV and a high dimensional baryon number violating coupling [8–10], where the Yukawa coupling(s) of the scalar(s) act as the source of CP-asymmetry. Apparently, this high dimensional baryon number violating coupling is generated via new physics operative beyond standard model electroweak theory. The mechanism of PSB is based on the idea that the required amount of baryon asymmetry of the universe can be generated below the scale of electroweak phase transition where the sphaleron has decoupled from the Hubble expansion rate. Although the proposal seems interesting it has not yet been incorporated in a realistic grand unified theory. Hence we attempt here to embed the proposal of PSB in a non-SUSY $SO(10)$ GUT with Pati-Salam (PS) symmetry and Left-Right (LR) symmetry as intermediate symmetry breaking steps.

A detail study of the literatures [11–18] gives an idea about many intriguing features of the $SO(10)$ grand unified theory (including both non-SUSY and SUSY). One of these features is

that when left-right gauge symmetry appears as an intermediate symmetry breaking step in a novel symmetry breaking chain, then seesaw mechanism can be naturally incorporated into it. In conventional seesaw models associated with thermal leptogenesis the mass scale for heavy RH Majorana neutrino is at 10^{10} GeV which makes it unsuitable for direct detectability at current accelerator experiments like LHC. Therefore, it is necessary to construct a theory having $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$ and $SU(2)_L \times SU(2)_R \times SU(4)_C$ gauge groups as intermediate symmetry breaking steps which results in low mass right-handed Majorana neutrinos along with W_R , Z' gauge bosons at TeV scale. At the same time it should be capable of explaining post-sphaleron baryogenesis elegantly along with other derivable predictions like proton decay and neutron-antineutron oscillation.

We intend to discuss TeV scale post-sphaleron baryogenesis, neutron-antineutron oscillation having mixing time close to the experimental limit with the Pati-Salam symmetry or $SO(10)$ GUT as mentioned in a recent work [19] slightly modifying the Higgs content where non-zero light neutrino masses can be accommodated via gauged extended inverse seesaw mechanism along with TeV scale W_R , Z' gauge bosons. As discussed in the work [19] the Dirac neutrino mass matrix is similar to the up-quark mass matrix even with low scale right-handed symmetry breaking. Though the details has been already discussed in the above mentioned work we briefly clarify the point as follows.

In non-SUSY $SO(10)$, the type I seesaw [20] contribution to neutrino mass is given by

$$m_\nu^I = -M_D M_R^{-1} M_D^T,$$

where M_D is the Dirac neutrino mass matrix, M_R is the Majorana neutrino mass matrix for right-handed neutrinos and is related to the right-handed symmetry breaking scale. The Dirac neutrino mass matrix and up-quark mass matrices are similar in a generic $SO(10)$ model that has high scale Pati-Salam symmetry as an intermediate breaking step relating quarks and leptons with each other. Hence, $M_D \simeq M_u$, which further implies that the τ -neutrino Dirac Yukawa coupling should be equal to top-quark Yukawa coupling. With $M_D \simeq M_u \simeq 100$ GeV, the sub-eV scale of light neutrino consistent with oscillation data requires the right-handed scale (seesaw scale) to be greater than 10^{13} GeV. Such high seesaw scale makes this idea difficult to be probed at any foreseeable laboratory experiments. Hence, as an alternative way, emphasizing on its verifiability at LHC, inverse seesaw mechanism [21, 22] has been proposed, with an extra $SO(10)$ fermion singlet S (in addition to the

existing fermion content of $SO(10)$), with light neutrino mass formula

$$m_\nu = \left(\frac{M_D}{M} \right) \mu \left(\frac{M_D}{M} \right)^T,$$

where M is the $N - S$ mixing matrix and μ is the small lepton number violating mass term for sterile neutrino S . The above relation can be recasted as

$$\left(\frac{m_\nu}{0.1 \text{ eV}} \right) = \left(\frac{M_D}{100 \text{ GeV}} \right)^2 \left(\frac{\mu}{\text{keV}} \right) \left(\frac{M}{10^4 \text{ GeV}} \right)^{-2}.$$

Hence, sub-eV mass for light neutrinos are consistent with $M_D \simeq M_u$ (or, $Y_D \simeq Y_t$) which is a generic predictions of high scale Pati-Salam symmetry and compatible with low right-handed symmetry breaking scale (M_R) since inverse seesaw formula is independent of M_R . We have utilised this particular property of low scale right-handed symmetry breaking in studying Post-sphaleron baryogenesis and neutron-antineutron oscillation even though a complete discussion on the origin of neutrino masses and mixing via low scale extended inverse seesaw has been omitted.

Here we sketch out the complete work of our paper. In Sec.II, we briefly discuss non-SUSY $SO(10)$ GUT with a novel symmetry breaking chain, having \mathcal{G}_{2213} and \mathcal{G}_{224} as intermediate symmetry breaking steps. In Sec.III we show how gauge coupling unification is achieved in our model. In Sec.IV we discuss the TeV scale post-sphaleron baryogenesis and embed it within the novel chain of non-SUSY $SO(10)$ model with the self-consistent model parameters. In Sec.V, we estimate the mixing time for neutron-antineutron oscillation. In Sec.VI, we present an idea how low mass scales for RH Majorana neutrino as well as right-handed gauge bosons W_R , Z' are allowed in the model, while explaining light neutrino masses via gauged extended seesaw mechanism. In Sec.VII we conclude our work with results and summary including a note on viability of the model at LHC.

II. THE MODEL

In this section we shall discuss the one-loop gauge coupling unification and estimate the proton life time including short distance enhancement factor to the $d = 6$ proton decay

operator by reviving the symmetry breaking chain [19]

$$\begin{aligned}
SO(10) &\xrightarrow{M_U} SU(2)_L \times SU(2)_R \times SU(4)_C \times D \quad [\mathcal{G}_{224D}, (g_{2L} = g_{2R})] \\
&\xrightarrow{M_P} SU(2)_L \times SU(2)_R \times SU(4)_C \quad [\mathcal{G}_{224}, (g_{2L} \neq g_{2R})] \\
&\xrightarrow{M_G} SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C \quad [\mathcal{G}_{2213}] \\
&\xrightarrow{M_\Omega} SU(2)_L \times U(1)_R \times U(1)_{B-L} \times SU(3)_C \quad [\mathcal{G}_{2113}] \\
&\xrightarrow{M_{B-L}} SU(2)_L \times U(1)_Y \times SU(3)_C \quad [\mathcal{G}_{SM} \equiv \mathcal{G}_{213}] \\
&\xrightarrow{M_Z} U(1)_{em} \times SU(3)_C \quad [\mathcal{G}_{13}].
\end{aligned} \tag{1}$$

The chain breaks in a sequence, where $SO(10)$ first breaks down to \mathcal{G}_{224D} , ($g_{2L} = g_{2R}$) after the Higgs representation $\langle(1, 1, 1)\rangle \subset \{54\}_H$ is given a VEV, then the spontaneous breakdown of D-parity occurs in \mathcal{G}_{224D} , ($g_{2L} = g_{2R}$) \rightarrow \mathcal{G}_{224} , ($g_{2L} \neq g_{2R}$) with the assignment of VEV to D-parity odd component $\langle(1, 1, 1)\rangle$ contained in the Higgs representation $\{210\}_H$. The decomposition of $\{210\}_H$ under \mathcal{G}_{224} is

$$\begin{aligned}
\{210\}_H &= (1, 1, 1) \oplus (2, 2, 20) \oplus (3, 1, 15) \oplus (1, 3, 15) \\
&\oplus (2, 2, 6) \oplus (1, 1, 15).
\end{aligned} \tag{2}$$

Spontaneous D-parity mechanism is aptly utilized here, since the theory allows low mass scale for right-handed Higgs fields around $\mathcal{O}(\text{TeV})$ while keeping all its left-handed components at D-parity breaking scale. Now assigning a VEV to the neutral component $\langle(1, 1, 15)\rangle \subset \{210\}_H$, the Pati-Salam symmetry (\mathcal{G}_{224}) breaks down to left-right symmetry (\mathcal{G}_{2213}). The next step of symmetry breaking $\mathcal{G}_{2213} \rightarrow \mathcal{G}_{2113}$ occurs via the VEV $\langle(1, 3, 0, 1)\rangle \subset \{210\}_H$. The right-handed gauge boson W_R acquires a mass in the range of few TeV and contributes sub-dominantly to neutrinoless double beta decay.

The most desirable symmetry breaking step $\mathcal{G}_{2113} \rightarrow \mathcal{G}_{213}$ is achieved by the $\{126\}_H$ of $SO(10)$ though we have added another Higgs representation $\{16\}_H$ for realization of gauged inverse seesaw mechanism operative at TeV scale. The decomposition of the Higgs $\{126\}_H$ under \mathcal{G}_{224} is

$$\{126\}_H = (3, 1, 10) \oplus (1, 3, \overline{10}) \oplus (2, 2, 15) \oplus (1, 1, 6) \tag{3}$$

As we have pointed earlier, due to D-parity mechanism, the right-handed triplet Higgs field $\Delta_R(1, 3, -2, 1)$ contained in $(3, 1, 10)$ gets its mass at TeV scale while its left-handed

partner $\Delta_L(3, 1, -2, 1)$ has its mass at D-parity breaking scale M_P . As a result of this symmetry breaking, the neutral component of right-handed gauge boson Z' gets its mass around $\mathcal{O}(\text{TeV})$ with the experimental bound $M_{W_R} \geq 2.5 \text{ TeV}$ [24, 25]. The final stage of symmetry breaking $\mathcal{G}_{2113} \rightarrow \mathcal{G}_{213}$ is carried out by giving VEV to the neutral component of SM Higgs doublet $\langle \phi^0(2, 1/2, 1) \rangle$ contained in the bidoublet $\Phi \subset \{10\}_H$.

We shall now check whether $SO(10)$ having TeV scale post-sphaleron baryogenesis, neutron-antineutron oscillation and gauged inverse seesaw mechanism is consistent with gauge coupling unification. It is found that the coupling constants unify at $(10^{17} - 10^{18.5})$ GeV with the Higgs fields $\{10\}_H + \{10\}'_H + \{16\}_H + \{126\}_H + \{210\}_H$. Some good reasons behind taking these Higgs fields are; firstly, the TeV scale post-sphaleron baryogenesis and neutron-antineutron oscillation can be well explained with these parameters while predicting W_R gauge boson in TeV range; secondly, it allows $B - L$ breaking (M_{B-L}) at TeV scale resulting Z' mass $\geq 1.6 \text{ TeV}$, moreover it explains tiny masses for light neutrinos consistent with neutrino oscillation data via TeV scale gauged inverse seesaw mechanism and LFV decays with branching ratios accessible to ongoing search experiments.

III. GAUGE COUPLING UNIFICATION AND PROTON DECAY

A. One-loop renormalization group equations (RGEs) for gauge coupling evolution

For simplicity, we consider only the one-loop renormalization group equations(RGEs) for gauge coupling evolution which can be written as

$$\mu \frac{d g_i}{d \mu} = \frac{a_i}{16\pi^2} g_i^3 \implies \frac{d \alpha_i^{-1}}{d t} = \frac{\mathbf{a}_i}{2\pi} \quad (4)$$

where, $t = \ln(\mu)$, $\alpha_i = g_i^2/(4\pi)$ is the fine structure constant, and \mathbf{a}_i is the one-loop beta coefficients derived for the the corresponding i^{th} gauge group for which coupling evolution has to be determined. Using the input parameters, electroweak mixing angle $\sin^2 \theta_W(M_Z) = 0.2312$, electromagnetic coupling constant $\alpha(M_Z) = 1/127.9$ and strong coupling constant $\alpha_S(M_Z) = 0.1187$ taken from PDG [3, 23] the values of three coupling con-

stants at electroweak scale $M_Z = 91.187$ GeV can be calculated precisely to be,

$$\begin{pmatrix} \alpha_{2L}(M_Z) \\ \alpha_{1Y}(M_Z) \\ \alpha_{3C}(M_Z) \end{pmatrix} = \begin{pmatrix} 0.033493^{+0.000042}_{-0.000038} \\ 0.016829 \pm 0.000017 \\ 0.118 \pm 0.003 \end{pmatrix}, \quad (5)$$

where $\{\alpha_{2L}(M_Z), \alpha_{1Y}(M_Z), \alpha_{3C}(M_Z)\}$ denote the fine structure constants for the SM gauge group $\mathcal{G}_{213} = SU(2)_L \times U(1)_Y \times SU(3)_C$.

B. Higgs content for the model and corresponding one-loop beta coefficients a_i

The Higgs contents for the model used in different ranges of mass scales under respective gauge symmetries (\mathcal{G}_I) with a particular symmetry breaking chain as considered in a recent work [19] where the prime interest was to keep the W_R , Z_R gauge bosons at TeV scale are as follows,

- (i) $\mu = \mathbf{M}_Z - \mathbf{M}_{\mathbf{B-L}} : G = \text{SM} = G_{213}, \text{ Higgs: } \Phi(2, 1/2, 1);$
 - (ii) $\mu = \mathbf{M}_{\mathbf{B-L}} - \mathbf{M}_{\mathbf{\Omega}} : G = G_{2113},$
Higgs: $\Phi_1(2, 1/2, 0, 1) \oplus \Phi_2(2, -1/2, 0, 1) \oplus \chi_R(1, 1/2, -1, 1) \oplus \Delta_R(1, 1, -2, 1);$
 - (iii) $\mu = \mathbf{M}_{\mathbf{\Omega}} - \mathbf{M}_{\mathbf{C}} : G = G_{2213},$
Higgs: $\Phi_1(2, 2, 0, 1) \oplus \Phi_2(2, 2, 0, 1) \oplus \chi_R(1, 2, -1, 1) \oplus \Delta_R(1, 3, -2, 1) \oplus \Omega_R(1, 3, 0, 1)$
- (6)

$$\begin{aligned}
\text{(iv)} \mu &= \mathbf{M}_C - \mathbf{M}_\xi : G = G_{224}, \\
&\text{Higgs: } \Phi_1(2, 2, 1)_{10} \oplus \Phi_2(2, 2, 1)_{10'} \oplus \Delta_R(1, 3, \overline{10})_{126} \oplus \chi_R(1, 2, \overline{4})_{16} \\
&\quad \oplus \Omega_R(1, 3, 15)_{210} \oplus \Sigma(1, 1, 15)_{210} \\
\text{(v)} \mu &= \mathbf{M}_\xi - \mathbf{M}_P : G = G'_{224}, \\
&\text{Higgs: } \Phi_1(2, 2, 1)_{10} \oplus \Phi_2(2, 2, 1)_{10'} \oplus \Delta_R(1, 3, \overline{10})_{126} \oplus \chi_R(1, 2, \overline{4})_{16} \\
&\quad \oplus \Omega_R(1, 3, 15)_{210} \oplus \Sigma(1, 1, 15)_{210} \oplus \xi(2, 2, 15)_{126} \\
\text{(vi)} \mu &= \mathbf{M}_P - \mathbf{M}_U : G = G_{224D}, \\
&\text{Higgs: } \Phi_1(2, 2, 1)_{10} \oplus \Phi_2(2, 2, 1)_{10'} \oplus \Delta_L(3, 1, 10)_{126} \oplus \Delta_R(1, 3, \overline{10})_{126} \\
&\quad \oplus \chi_L(2, 1, 4)_{16} \oplus \chi_R(1, 2, \overline{4})_{16} \oplus \Omega_L(3, 1, 15)_{210} \oplus \Omega_R(1, 3, 15)_{210} \\
&\quad \oplus \Sigma(1, 1, 15)_{210} \oplus \xi(2, 2, 15)_{126} \oplus \sigma(1, 1, 1)_{210}.
\end{aligned} \tag{7}$$

Here we find two categories of Higgs spectrum; **Model-I** having Higgs spectrum as given in eqn.(6) and eqn.(7) excluding the bitriplet Higgs scalar which estimates a proton life time that is far from the reach of search experiments and **Model-II** having the same Higgs spectrum, including the bitriplet Higgs scalar $(3, 3, 1) \subset \mathcal{G}_{224}$ from mass scale M_C onwards which estimates a proton life time very close to the experimental limit. Thus **Model-II** serves our purpose.

The one-loop beta coefficients are found to be the same for both the models at mass scale ranges $M_Z - M_{B-L}$, $M_{B-L} - M_\Omega$, and $M_\Omega - M_C$ i.e.,

$$\begin{aligned}
\text{(i)} \mu &= \mathbf{M}_Z - \mathbf{M}_{B-L} : G = \text{SM} = G_{2_L 1_Y 3_C}, \quad \mathbf{a}_i = (-19/6, 41/10, -7) \\
\text{(ii)} \mu &= \mathbf{M}_{B-L} - \mathbf{M}_\Omega : G = G_{2_L 1_{R1(B-L)} 3_C}, \quad \mathbf{a}_i = (-3, 19/4, 37/8, -7) \\
\text{(iii)} \mu &= \mathbf{M}_\Omega - \mathbf{M}_C : G = G_{2_L 2_{R1(B-L)} 3_C}, \quad \mathbf{a}_i = (-8/3, -2/3, 23/4, -7),
\end{aligned} \tag{8}$$

whereas, they differ at Pati-Salam scale M_C to the Unification scale M_U as shown in Table.I.

The gauge coupling unification for this work is shown in Fig.1 with the allowed mass scales desirable for our model predictions,

$$\begin{aligned}
M_{B-L} &= 4 - 7 \text{ TeV}, \quad M_\Omega = 10 \text{ TeV}, \quad M_C = 10^5 - 10^6 \text{ GeV}, \\
M_P &\simeq 10^{15.65} \text{ GeV} \text{ and } M_G \simeq 10^{18.65} \text{ GeV}.
\end{aligned} \tag{9}$$

G_I	Mass ranges	$\mathbf{a_i}$ for Model-I	$\mathbf{a_i}$ for Model-II
$G_{2_L 2_R 4_C}$	$M_C - M_\xi$	$\begin{pmatrix} -8/3 \\ 29/3 \\ -14/3 \end{pmatrix}$	$\begin{pmatrix} -2/3 \\ 35/2 \\ -14/3 \end{pmatrix}$
$G_{2_L 2_R 4_C}$	$M_\xi - M_P$	$\begin{pmatrix} 7/3 \\ 44/3 \\ 2/3 \end{pmatrix}$	$\begin{pmatrix} -12/3 \\ 35/3 \\ -14/3 \end{pmatrix}$
$G_{2_L 2_R 4_C D}$	$M_P - M_U$	$\begin{pmatrix} 44/3 \\ 44/3 \\ 6 \end{pmatrix}$	$\begin{pmatrix} 35/3 \\ 35/3 \\ 2/3 \end{pmatrix}$

TABLE I: One-loop beta coefficients for different gauge coupling evolutions, without Bitriplet Higgs scalar in **Model-I** and with a Bitriplet Higgs scalar (3,3,1) under the Pati-Salam group $SU(2)_L \times SU(2)_R \times SU(4)_C$ in **Model-II**.

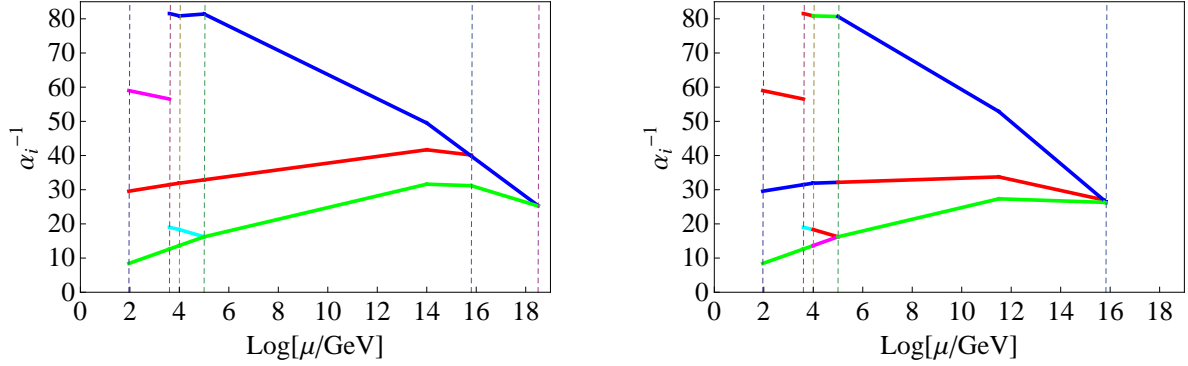


FIG. 1: Gauge coupling evolution plot having TeV scale W_R, Z_R bosons where $M_U = 2.65 \times 10^{15.8}$ GeV

C. Estimation of Proton life time for $p \rightarrow \pi^0 e^+$

The decay rate for the gauge boson mediated proton decay in the channel $p \rightarrow \pi^0 e^+$ including strong and electroweak renormalization effects on the $d = 6$ operator starting

from the GUT scale to the proton mass (i.e, 1 GeV) [26, 27] comes out to be

$$\Gamma(p \rightarrow \pi^0 e^+) = \frac{\pi}{4} A_L^2 \frac{|\bar{\alpha}_H|^2 m_p \alpha_U^2}{f_\pi^2 M_U^4} (1 + \mathcal{F} + \mathcal{D})^2 \mathcal{R}. \quad (10)$$

In the eq. (10), $A_L = 1.25$ is renormalization factor from the electroweak scale to the proton mass, $\mathcal{D} = 0.81$, $\mathcal{F} = 0.44$, $\bar{\alpha}_H = -0.011 \text{ GeV}^3$, and $f_\pi = 139 \text{ MeV}$ which have been extracted as phenomenological parameters by the chiral perturbation theory and lattice gauge theory. Also $m_p = 938.3 \text{ MeV}$ is the proton mass, and $\alpha_U \equiv \alpha_G$ is the gauge fine structure constant derived at the GUT scale. It is worth to note here that the renormalization factor $\mathcal{R} = \left[(A_{SR}^2 + A_{SL}^2) (1 + |V_{ud}|^2)^2 \right]$ for $SO(10)$, $V_{ud} = 0.974$ with $A_{SL}(A_{SR})$ being the short-distance renormalization factor in the left (right) sectors, and V_{ud} is the $(1, 1)$ element of V_{CKM} for quark mixings.

After re-expressing $\alpha_H = \bar{\alpha}_H (1 + \mathcal{F} + \mathcal{D}) = 0.012 \text{ GeV}^3$, and $\mathcal{A}_R \simeq \mathcal{A}_L \mathcal{A}_{SL} \simeq \mathcal{A}_L \mathcal{A}_{SR}$, the proton life time can be expressed as

$$\tau_p = \Gamma^{-1}(p \rightarrow \pi^0 e^+) = \frac{4}{\pi} \frac{f_\pi^2 M_U^4}{m_p \alpha_U^2} \frac{1}{\alpha_H^2 \mathcal{A}_R^2 \mathcal{F}_q}, \quad (11)$$

where $\mathcal{F}_q \simeq 7.6$.

Short distance enhancement factor \mathcal{A}_{SL} extrapolated from GUT scale to 1 GeV:

For estimating proton decay rate in the channel $p \rightarrow e^+ \pi^0$ having dimension-6 operator, one needs to extrapolate the operator from the GUT scale physics to the low energy physics at the scale of $m_p = 1 \text{ GeV}$ [28–30]. With the particular symmetry breaking chain allowed in the non-SUSY $SO(10)$ model (following the ref. [30]), the whole energy range can be separated into following parts

- I. from non-SUSY $SO(10)$ GUT scale, M_U , to the Pati-Salam symmetry with D-parity (\mathcal{G}_{224D} , $g_{2L} = g_{2R}$) invariance scale, M_P ,
- II. from M_P to the Pati-Salam symmetry without D-parity (\mathcal{G}_{224} , $g_{2L} \neq g_{2R}$) scale M_C ,
- III. from M_C to $SU(4)_C$ breaking scale, M_Ω , where we have left-right symmetric model (LRSM) \mathcal{G}_{2213} ,
- IV. from left-right symmetry breaking scale (M_Ω) to \mathcal{G}_{2113} scale (M_{B-L})
- V. from \mathcal{G}_{2113} scale (M_{B-L}) to standard model \mathcal{G}_{213} ,

V. from standard model to 1 GeV.

As discussed in refs. [28–30], the enhancement factor below SM for the $LLLL$ operator is

$$\mathcal{A}'_L = \left[\frac{\alpha_s(1 \text{ GeV})}{\alpha_s(m_t)} \right]^{-\frac{4}{2 \cdot (-11 + \frac{2}{3} n_f)}},$$

where, n_f denotes the number of quark flavors at the particular energy scale of our interest. Neglecting the effect due to α_{2L} and α_Y since their contributions are suppressed as compared to the strong coupling effect α_s , this enhancement factor can be expressed in a more explicit manner as

$$\mathcal{A}'_L = \left[\frac{\alpha_s(1 \text{ GeV})}{\alpha_s(m_c)} \right]^{2/9} \left[\frac{\alpha_s(m_c)}{\alpha_s(m_b)} \right]^{6/25} \left[\frac{\alpha_s(m_b)}{\alpha_s(m_t)} \right]^{6/23}. \quad (12)$$

Since the model considered here is non-supersymmetric version of $SO(10)$ GUT, all other enhancement factors can be written in the same way as

$$\mathcal{A}_{SL}^{\text{SM}} = \left[\frac{\alpha_i(m_t)}{\alpha_i(M_R^0)} \right]^{-\frac{\gamma_i}{2\mathbf{a}_i}}, \quad (13)$$

with γ_i (\mathbf{a}_i) as the anomalous dimension (one-loop beta coefficients) for the corresponding gauge group $i = SU(2)_L, U(1)_Y, SU(3)_C$. Similarly, one can write the enhancement factor valid for \mathcal{G}_{2113} , \mathcal{G}_{2213} , \mathcal{G}_{224} , and \mathcal{G}_{224D} as

$$\begin{aligned} \mathcal{A}_{SL}^{2113} &= \left[\frac{\alpha_i(M_R^0)}{\alpha_i(M_R^+)} \right]^{-\frac{\gamma_i}{2\mathbf{a}_i}}, \text{ with } i = SU(2)_L, U(1)_R, U(1)_{B-L}, SU(3)_C, \\ \mathcal{A}_{SL}^{2213} &= \left[\frac{\alpha_i(M_R^+)}{\alpha_i(M_C)} \right]^{-\frac{\gamma_i}{2\mathbf{a}_i}}, \text{ with } i = SU(2)_L, SU(2)_R, U(1)_{B-L}, SU(3)_C, \\ \mathcal{A}_{SL}^{224} &= \left[\frac{\alpha_i(M_C)}{\alpha_i(M_P)} \right]^{-\frac{\gamma_i}{2\mathbf{a}_i}}, \text{ with } i = SU(2)_L, SU(2)_R, SU(4)_C, \\ \mathcal{A}_{SL}^{224D} &= \left[\frac{\alpha_i(M_P)}{\alpha_i(M_U)} \right]^{-\frac{\gamma_i}{2\mathbf{a}_i}}, \text{ with } i = SU(2)_L, SU(2)_R, SU(4)_C \text{ with D-parity.} \end{aligned}$$

Hence, the complete short distance enhancement renormalization factor for this $d = 6$ proton decay operator is found to be

$$\mathcal{A}_{SL} = \mathcal{A}_{SL}^{\text{SM}} \cdot \mathcal{A}_{SL}^{2113} \cdot \mathcal{A}_{SL}^{2213} \cdot \mathcal{A}_{SL}^{224} \cdot \mathcal{A}_{SL}^{224D}. \quad (14)$$

We have earnestly followed the prescription given in ref.[28, 29] for the derivation of anomalous dimension for the effective $d = 6(LLLL)$ proton decay operator. With a choice

of TeV scale particle spectrum used in our model, the unification scale is found to be $M_U = 2.65 \times 10^{18.5}$ GeV for **Model-I** and $M_U = 10^{15.8}$ GeV for **Model-II**. We have estimated the factor $\mathcal{A}_R = \mathcal{A}_L \cdot \mathcal{A}_{SL}$, approximately, to be 4.36 with the value of long distance renormalization factor $A_L = 1.25$ which is the same for both the models.

With these input parameters, the model under consideration predicts the proton life time to be

$$\tau(p \rightarrow e^+ \pi^0) = 2.6 \times 10^{34} \text{ yrs}$$

that is closer to the latest Super-Kamiokande experimental bound [31, 32]

$$\tau(p \rightarrow e^+ \pi^0)|_{SK,2011} > 8.2 \times 10^{33} \text{ yrs}, \quad (15)$$

and ably supports planned experiments that can reach a bound [33]

$$\begin{aligned} \tau(p \rightarrow e^+ \pi^0)|_{HK,2025} &> 9.0 \times 10^{34} \text{ yrs} \\ \tau(p \rightarrow e^+ \pi^0)|_{HK,2040} &> 2.0 \times 10^{35} \text{ yrs} \end{aligned} \quad (16)$$

IV. TEV SCALE POST-SPHALERON BARYOGENESIS

A. Basic interaction terms

As already discussed in Sec. III, Pati-Salam symmetry survives till few 100 TeV scale playing an important role in the explanation of baryogenesis mechanism and neutron-antineutron oscillation. We need to know all the basic interactions using quarks and di-quarks under high scale Pati-Salam symmetry as well as under low scale SM like interactions around TeV scale in order to explain the above said phenomena successfully. For that, we take a look at the decomposition of the Pati-Salam Higgs representation $\Delta_R(1, 3, \overline{10})$ under left-right symmetry group $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$ and the SM gauge group

$$SU(2)_L \times U(1)_Y \times SU(3)_C$$

$$\Delta(1, 3, \overline{10}) = \{ \Delta_{\ell\ell}(1, 3, -2, 1) \oplus \Delta_{q\ell}(1, 3, -2/3, 3^*) \oplus \Delta_{qq}(1, 3, 2/3, 6^*) \}$$

under $\mathcal{G}_{2_L 2_R 1_{B-L} 3_C}$, (17)

$$\begin{aligned} &\supset \Delta_{\nu\nu}(1, 0, 1) \oplus \Delta_{\nu e}(1, 1, 1) \oplus \Delta_{ee}(1, 2, 1) \\ &\oplus \Delta_{u\nu}(1, -2/3, 3^*) \oplus \Delta_{de}(1, 1/3, 3^*) \oplus \Delta_{ue}(1, 1/3, 3^*) \oplus \Delta_{d\nu}(1, 1/3, 3^*) \\ &\oplus \Delta_{uu}(1, -4/3, 6^*) \oplus \Delta_{ud}(1, -1/3, 6^*) \oplus \Delta_{dd}(1, 2/3, 6^*) \end{aligned}$$

under $\mathcal{G}_{2_L 1_Y 3_C}$, (18)

where the electric charge is expressed in terms of the generators of the SM group and left-right symmetric group as,

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2} = T_{3L} + Y . \quad (19)$$

Since the fields $\Delta_{\nu\nu}(S)$, Δ_{uu} , Δ_{ud} , Δ_{ud} and quark fields are mainly responsible for non-zero baryon asymmetry and neutron-antineutron oscillation, we need to know the exact interactions among them. The desirable interaction Lagrangian for diquark Higgs scalars with the SM quarks at TeV scale which will yield observable neutron-antineutron oscillation and post-sphaleron baryogenesis is

$$\begin{aligned} \mathcal{L} &\supset \frac{f_{ij}}{2} \Delta_{dd} d_i d_j + \frac{h_{ij}}{2} \Delta_{uu} u_i u_j + \frac{g_{ij}}{2\sqrt{2}} \Delta_{ud} (u_i d_j + d_i u_j) \\ &+ \frac{\lambda}{2} \Delta_{\nu\nu} \Delta_{dd} \Delta_{ud} \Delta_{ud} + \frac{\lambda'}{2} \Delta_{\nu\nu} \Delta_{uu} \Delta_{dd} \Delta_{dd} + \text{h.c.} \\ &\subset F \left(\psi_{Ra}^T C^{-1} \tau_2 \vec{\tau} \cdot \Delta_{ab}^\dagger \psi_{Rb} + \text{L} \leftrightarrow \text{R} \right) + \text{h.c. under } \mathcal{G}_{224} , \end{aligned} \quad (20)$$

where F , f , h , g are the Majorana couplings and τ is the generator for $SU(2)$ group.

Within the $SO(10)$ framework, the Yukawa couplings obey the boundary condition, $f_{ij} = h_{ij} = g_{ij}$ in the $SU(2)_L \times SU(2)_R \times SU(4)_C \times D$ limit and the same holds true for quartic Higgs couplings $\lambda = \lambda'$ as well. All fermions are right-handed (when chiral projection on the operator is suppressed) and a fermion field under the high scale Pati-Salam symmetry \mathcal{G}_{224} transforms as,

$$\psi_{L,R} = \begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & e \end{pmatrix}_{L,R} \quad (21)$$

The diquark Higgs scalars transforming under the SM gauge group $SU(2)_L \times U(1)_Y \times SU(3)_C$ are denoted with quantum numbers as,

$$\Delta_{\nu\nu}(1, 0, 1), \Delta_{u^c u^c}(1, -4/3, 6^*), \Delta_{d^c d^c}(1, 2/3, 6^*), \text{ and } \Delta_{u^c d^c}(1, -1/3, 6^*). \quad (22)$$

It is clear from eqn (20) that the Higgs field $\Delta_{\nu\nu}(1, 0, 1) \subset \Delta_R(1, 3, -2, 1) \subset (1, 3, \overline{10})$ is a neutral complex field. The breaking of $\mathcal{G}_{2113} \rightarrow \mathcal{G}_{213}$ is achieved by assigning a VEV to its neutral component $\Delta_{\nu\nu} \subset \Delta_R(1, 0, -2, 1)$. Its real component acquires a VEV in the ground state which can be represented as $\Delta_{\nu\nu} = v_{B-L} + \frac{1}{\sqrt{2}}(S_r + i\rho)$ while the field ρ gets absorbed by the gauge boson corresponding to the gauge group $U(1)_{B-L}$. Therefore, the remaining real scalar field S_r is indeed the physical Higgs particle which serves our purpose of explaining post-sphaleron baryogenesis and neutron-antineutron oscillation.

B. General expression for CP-asymmetry

Without loss of generality, if we consider the particle and antiparticle decay modes of S_r (S_r being its own antiparticle) i.e, $S_r \rightarrow u^c d^c u^c d^c d^c d^c$ which gives a change of baryon number $\Delta B_{(S_r \rightarrow 6q^c)} = +2$, and $S_r \rightarrow \bar{u}^c \bar{d}^c \bar{u}^c \bar{d}^c \bar{d}^c \bar{d}^c$ which gives $\Delta B_{(S_r \rightarrow 6\bar{q}^c)} = -2$, then the CP-asymmetry in baryon number produced by these decays can be quantified as,

$$\begin{aligned} \varepsilon_{CP} &= \frac{\Delta B_{(S_r \rightarrow 6q^c)} \Gamma(S_r \rightarrow 6q^c)}{\Gamma_{\text{tot}}} + \frac{\Delta B_{(S_r \rightarrow 6\bar{q}^c)} \Gamma(S_r \rightarrow 6\bar{q}^c)}{\Gamma_{\text{tot}}}, \\ &= \frac{(+2) \Gamma(S_r \rightarrow 6q^c) + (-2) \Gamma(S_r \rightarrow 6\bar{q}^c)}{\Gamma_{\text{tot}}} = 2 \frac{\Gamma - \bar{\Gamma}}{\Gamma_{\text{tot}}}, \end{aligned} \quad (23)$$

where $\Gamma_{\text{tot}} = \Gamma + \bar{\Gamma}$ is the total decay rate with $\Gamma \equiv \Gamma(S_r \rightarrow 6q^c)$ and $\bar{\Gamma} \equiv \Gamma(S_r \rightarrow 6\bar{q}^c)$. It is evident from eqn (23) that we need divergent partial decay rates for particle and antiparticle decays in order to produce correct amount of baryon asymmetry and hence we should derive the general conditions under which Γ and $\bar{\Gamma}$ can be different. It is worth to mention here that the other decay modes of S_r have been ignored for simplicity by adjusting the corresponding couplings involved in the respective decay modes. In generic situations where the theory is CPT-conserving, there can never be a difference between Γ and $\bar{\Gamma}$ if one considers only the tree-level process depicted in Fig. 2 since $\Gamma = \bar{\Gamma}$ at tree level. It is found that the nonzero contribution to ε_{CP} comes from the interference between the tree-level graph (shown in Fig. 2) and the one-loop corrections (shown in Fig. 3).

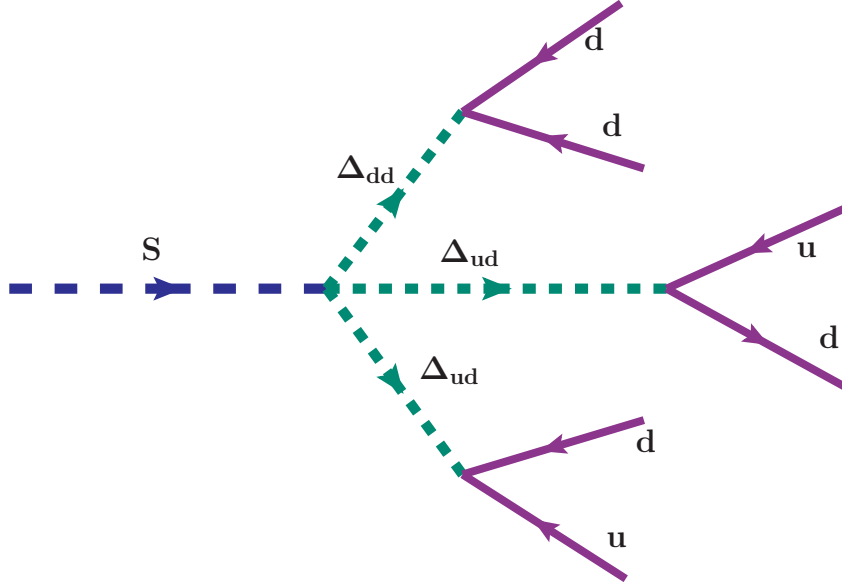


FIG. 2: Feynman diagram representing the decay of $S \rightarrow 6q$ at tree level in order to explain post-Sphaleron baryogenesis operative at TeV scale. Since S is a real scalar field, the decay mode $S \rightarrow 6\bar{q}$ is possible by reversing the arrow direction of the quark field.

C. Constraints on post-Sphaleron baryogenesis

Here we illustrate how post-Sphaleron baryogenesis is slightly different from any other standard baryogenesis process. For post-Sphaleron baryogenesis to be successful in explaining the required matter-antimatter asymmetry of our Universe, few extra conditions must be satisfied by the model parameters along with the *Sakharov conditions* that says, particle interaction must **(i)** violate baryon number, B , **(ii)** violate C and CP , and **(iii)** be out of thermal equilibrium. Firstly, the S_r Higgs scalar should be lighter than other members contained in the Pati-Salam multiplet $(1, 3, \overline{10})$ i.e, the diquark Higgs scalars Δ_{qq} so that the baryon number conserving decays involving on-shell Δ_{qq} are kinematically forbidden. Secondly, the out of equilibrium baryon number violating decays should occur after the electroweak phase transition so that it will not be affected by the Sphaleron processes which is proactive at $>\text{TeV}$ scale. We make it a point here that ref. [9] neatly elaborates the mechanism of post-sphaleron baryogenesis.

D. Out of equilibrium condition

For effectively creating the baryon asymmetry of the universe via post-Sphaleron baryogenesis, the decays of $\Gamma(S_r \rightarrow 6q^c)$ should satisfy the out of equilibrium condition, which is described by $\Gamma_{S_r} \lesssim H(T)$ where $\Gamma = \Gamma(S_r \rightarrow 6q^c) = \frac{36}{(2\pi)^9} \frac{(\text{Tr}[f^\dagger f])^3 \lambda^2 M_S^{13}}{6M_\Delta^{12}}$ is the total decay width and $H \simeq 1.66\sqrt{g_s^*} \frac{T^2}{M_{\text{Pl}}}$, is the Hubble parameter with the reduced Planck mass $M_{\text{Pl}} \simeq 1.2 \times 10^{18} \text{ GeV}$ and g_s^* is the number of relativistic degrees of freedom. In order to satisfy the out of equilibrium condition, we should have

$$\begin{aligned} \Gamma_{S_r} &\simeq H \big|_{(T=T_d)} \\ \Rightarrow T_d &= \left[\frac{36 \lambda^2 (\text{Tr}[f^\dagger f])^3 M_{\text{Pl}} M_S^{13}}{(2\pi)^9 1.66 g_*^{1/2} (6M_\Delta)^{12}} \right]^{1/2} \simeq 6.1 \times \left(\frac{M_S^{13}}{M_\Delta^{12}} \right)^{1/2} \text{ GeV}^{1/2} \end{aligned} \quad (24)$$

To illustrate the mechanism of post-sphaleron baryogenesis, we require extra fields Δ_{uu} , Δ_{ud} and Δ_{dd} as color sextets and $SU(2)_L$ singlet scalar bosons that couple to the right-handed quarks contained in the Pati-Salam multiplet $(1, 3, \overline{10})$. For set of model parameters $M_S = 500 \text{ GeV}$, $M_\Delta \simeq 1000 \text{ GeV}$, the decoupling temperature is found to be 2 GeV which is well below the EW scale where the Sphaleron has been decoupled. Hence, it is inferred from the above equation that the decay of S goes out of equilibrium around $T \simeq M_S$. Below this temperature ($T < M_S$), the decay rate falls very rapidly as the temperature cools down.

E. Estimation of net baryon asymmetry

Now we concentrate on estimating the CP-asymmetry coming from the interference term between the tree level and the one-loop level diagrams for the decay of S_r which is shown in Fig.2 and Fig.3 respectively. For discussion on baryon number violation in the loop diagram and necessary derivation of the interference diagram, interested readers may go through reference [9]. In the present work, we only check whether or not the representative set of model parameters provide the correct number for the required baryon asymmetry of the universe. Hence, without going deep into the derivation, we simply note here down, the calculated CP-asymmetry for post-sphaleron baryogenesis via decay of S_r with baryon

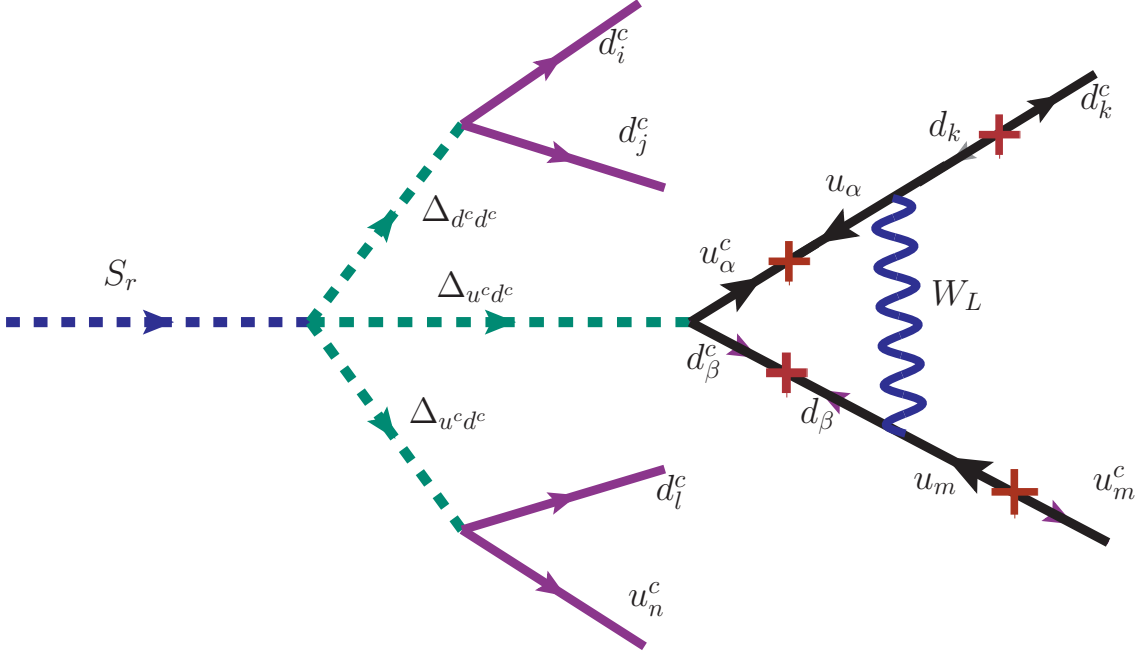


FIG. 3: Feynman graphs of the one-loop vertex correction for $\Gamma(S_r \rightarrow 6q^c)$.

number violating interactions.

$$\begin{aligned} \varepsilon_{\text{wave}} \simeq & \frac{g^2}{64\pi \text{Tr}(f^\dagger f)} f_{j\alpha} V_{j\beta}^* f_{i\alpha} \delta_{i3} \frac{m_t m_j}{m_t^2 - m_j^2} \sqrt{\left(1 - \frac{m_W^2}{m_t^2} + \frac{m_\beta^2}{m_t^2}\right)^2 - 4 \frac{m_\beta^2}{m_t^2}} \\ & \times \left[2 \left(1 - \frac{m_W^2}{m_t^2} + \frac{m_\beta^2}{m_t^2}\right) + \left(1 + \frac{m_\beta^2}{m_t^2}\right) \left(\frac{m_t^2}{m_W^2} + \frac{m_\beta^2}{m_t^2} - 1\right) - 4 \frac{m_\beta^2}{m_W^2} \right], \end{aligned} \quad (25)$$

$$\varepsilon_{\text{vertex}} \simeq \frac{g^2}{32\pi \text{Tr}(f^\dagger f)} f_{i\beta} V_{i\beta}^* f_{i\alpha} \delta_{i3} \frac{m_j m_\beta}{m_W^2} \left[1 + \frac{9m_W^2}{M_S^2} \ln \left(1 + \frac{M_S^2}{3m_W^2}\right) \right], \quad (26)$$

$$\varepsilon_{\text{CP}} = \varepsilon_{\text{wave}} + \varepsilon_{\text{vertex}}. \quad (27)$$

Here the expression in eq.(25) represents the CP-asymmetry coming from interference between the tree and one-loop self energy diagram while the expression in eq.(26) represents the CP-asymmetry due to interference of the tree and one-loop vertex diagram (see ref.[9] for details). In the above expression, V is the well known CKM matrix in the quark sector, i, j correspond to the up-quark indices u, c, t while α, β represent to down-quark indices d, s, b . Sum over repeated indices (Einstein convention) is implicitly assumed here. The δ_{i3} is due to the fact that the CP asymmetry is non-zero only when we have a top quark in the final state (since only the CKM elements involving third generation have a large imaginary part).

As mentioned earlier, the mechanism of post-sphaleron baryogenesis provides a natural

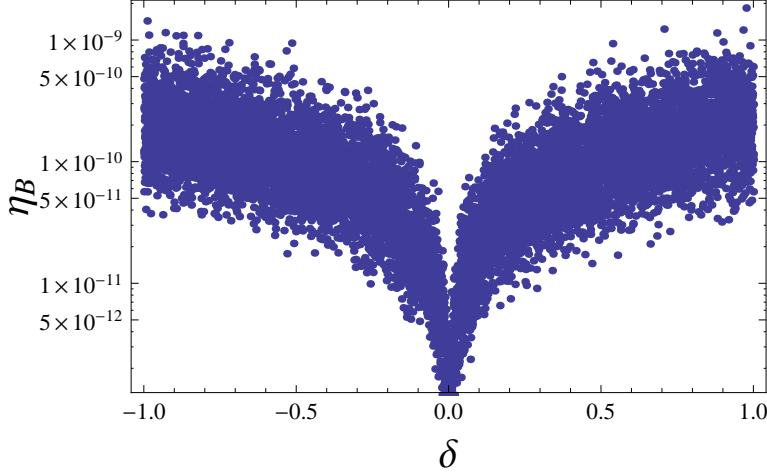


FIG. 4: Estimation of final baryon asymmetry in terms of CP-asymmetry with overall phase δ contained in the CKM mixing matrix.

explanation for the observed baryon asymmetry of our universe i.e, $\eta_B \simeq 10^{-10}$. Using $m_c = 1.27$ GeV, $m_b = 4.25$ GeV, $m_t = 172$ GeV, CKM mixing elements V_{CKM} and Yukawa couplings relevant for color scalar particles in their allowed range, the CP-asymmetry via the decay of S_r through loop diagrams with the exchanges of W^\pm bosons is estimated to be 10^{-8} . A further dilution of the baryon asymmetry arises from the fact that $T_d \ll M_S$, since the decay of S_r releases entropy into the universe. As a result the final baryon asymmetry, taking into account the dilution factor, becomes

$$\eta_B = \varepsilon_{CP} \times \left(\frac{T_d}{M_S} \right), \quad (28)$$

where T_d is the decoupling temperature of the color scalar and M_S is the mass of the scalar. The condition $T_d/M_S \geq 10^{-2}$, otherwise leads to suppressed baryon asymmetry, which finally results a baryon asymmetry in the range of 10^{-10} . The scatter plot between the final baryon asymmetry including dilution factor (η_B) with this phase (δ_{i3}) is shown in Fig. 4.

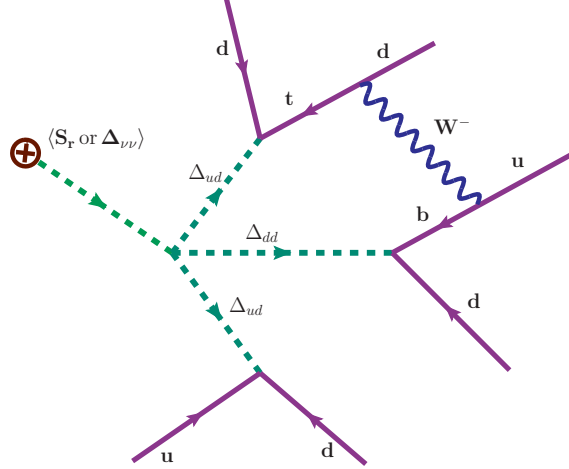


FIG. 5: Loop contributions to neutron-antineutron oscillation in the post-Sphaleron baryogenesis operative at TeV scale.

V. OBSERVABLE NEUTRON-ANTINEUTRON OSCILLATION WITH TEV SCALE DIQUARK HIGGS SCALARS:

A. Feynman amplitudes for neutron-antineutron oscillation

We consider the contributions arising only from the RH diquark Higgs fields having masses at TeV scale while ignoring the contributions from LH diquark Higgs fields since they have masses at around eV range. The Feynman diagrams contributing to the neutron-antineutron oscillation are shown in Fig. 5 (loop-diagram), Fig. 6(a) and Fig. 6(b). Our prime goal is to estimate the mixing time for this loop diagram, clarifying why we have suppressed other contributions within our model parameters.

There are two types of contributions to $n - \bar{n}$ oscillation in the right-handed sector at loop level (i) one involving one $u^c u^c$ -type and two $d^c d^c$ -type, (ii) other one involving one $d^c d^c$ -type and two $u^c d^c$ -type Δ -bosons. The Feynman amplitude for the second type of contribution where one needs to change the two b^c quarks to two d^c quarks from the already generated effective operator $u^c d^c b^c u^c d^c b^c$ via a second order weak interactions (given in Fig. 5) can be written as,

$$\mathcal{A}_{n-\bar{n}}^{1\text{-loop}} \simeq \frac{(f_{ud})_{11} (f_{ud})_{13} (f_{dd})_{13}}{M_{u^c d^c}^4 M_{d^c d^c}^2} \frac{\lambda v_{B-L}}{(16\pi^2)^2} \frac{g^4 V_{td}^2 m_b^2 m_t^2}{M_{W_L}^4} \log\left(\frac{m_b^2}{M_{W_L}^2}\right) \quad (29)$$

And, the Feynman amplitude for tree level processes shown in Fig. 6(a) and Fig. 6(b) (which

are suppressed with the choice of our model parameters), can be written as,

$$\begin{aligned}\mathcal{A}_{n-\bar{n}}^{\text{tree}} &= \mathcal{A}_{n-\bar{n}}^{(a)} + \mathcal{A}_{n-\bar{n}}^{(b)} \\ &\simeq \frac{(f_{dd})_{11} (f_{ud})_{11}^2 \lambda v_{B-L}}{M_{u^c d^c}^4 M_{d^c d^c}^2} + \frac{(f_{uu})_{11} (f_{dd})_{11}^2 \lambda v_{B-L}}{M_{d^c d^c}^4 M_{u^c u^c}^2}\end{aligned}\quad (30)$$

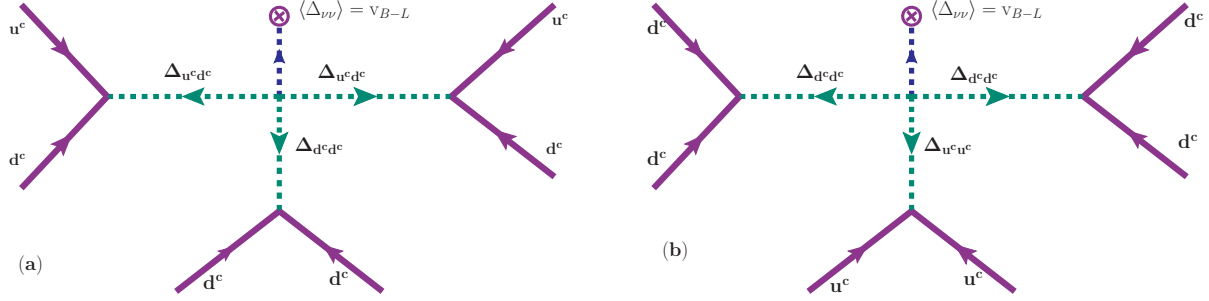


FIG. 6: Feynman diagrams contributing to neutron-antineutron oscillation. The figure in *left-panel* involves two $\Delta_{u^c d^c}$ and one $\Delta_{d^c d^c}$ bosons whereas the figure in *right-panel* involves two $\Delta_{d^c d^c}$ and one $\Delta_{u^c u^c}$ bosons. The structure of the theory is such that these tree-level contributions are suppressed in the present work.

B. Prediction for neutron-antineutron mixing time $\tau_{n-\bar{n}}$

Before estimating the $n - \bar{n}$ oscillation mixing time one should carefully fix the input parameters in order to satisfy flavor changing neutral current (FCNC) constraints and to give correct amount of baryon asymmetry of the universe. For example, using diquark sextet Higgs scalar mass around TeV scale, the corresponding Yukawa coupling $(f_{dd})_{11} \simeq 0.001 - 0.1$ along with other allowed range of model parameters contradicts the FCNC constraints and hampers post-sphaleron baryogenesis even though it predicts neutron-antineutron oscillation time (as shown in Fig. 6) within the experimental search limits. So this means that one has to choose the Majorana Yukawa coupling f accordingly. Now we briefly discuss how this choice of f can be achieved within the framework of SO(10) (elaborated in ref [19]).

It is found in ref [19] that all charged fermion masses and CKM mixing can be fitted well at GUT scale within the framework of SO(10) with two kinds of structures; I) with single Higgs representation 126_H , II) with two Higgs representations 126_H , $126'_H$. As it has been derived, structure-I with Yukawa coupling $f_{126_H} = \text{diag}(0.0236, -0.38, 1.5)$ estimates

$n - \bar{n}$ oscillation mixing time to be 10^9 secs which doesn't serve our purpose. Rather we consider structure-II where the dominant contribution to $n - \bar{n}$ oscillation comes from the loop diagram while suppressing the tree level contribution. This choice of having two Higgs 126_H , $126'_H$ not only fits fermion masses at GUT scale, but also allows RH neutrino Majorana mass and hence corresponding Yukawa coupling $f_{126'_H}$ as per our requirement. Due to the second Higgs representation $126'$ with its Yukawa coupling f' to fermions we get $v_{\xi'} = 1 - 100$ MeV following the same procedure, provided all other components are at the GUT scale except $\xi'(2, 2, 15)$ which is at the intermediate scale $M_{\xi'} = 10^{13} - 10^{14}$ GeV. By treating the mass of $\xi(2, 2, 15) \subset 126$ to remain at its natural GUT-scale value, its induced VEV is negligible and precision unification with large GUT scale value is unaffected except for phenomenologically inconsequential additional threshold effects. Then defining $F = f'v_{\xi'}$ gives exactly the same fit to the GUT scale fermion masses and mixings but now with the diagonal structure $f'_i = (0.0236, -0.38, 1.5)$. But since $\langle \Delta'_R \rangle = 0$ and only $\Delta_R \subset 126_H$ with VEV v_R is used to break G_{2113} , the coupling f and hence M_N are allowed to have any 3×3 form without any restriction. In order to suppress the tree level contributions to $n - \bar{n}$ oscillation as shown in Fig.6 which otherwise causes problem in baryon asymmetry, we particularly choose the Majorana coupling f_{dd} as per our requirement, i.e, $f_{dd11} \leq 10^{-5}$.

f_{13}	g_{11}	g_{13}	λ	$M_{\Delta ud}$ (GeV)	$M_{\Delta dd}$ (GeV)	$\tau_{n-\bar{n}}$ (sec)
0.001	0.01	0.01	0.1	10^3	10^4	3.96×10^8
0.001	0.01	0.01	0.1	10^3	10^5	8.72×10^{10}
0.001	0.01	0.01	1	10^3	10^5	3.29×10^9
0.001	0.001	0.001	0.1	10^3	10^4	4.42×10^{10}

TABLE II: Numerical estimation of neutrino-antineutrino oscillation time

Using this particular choice of Yukawa couplings i.e, $f_{dd11}, f_{dd22}, \leq 10^{-5}$ and others in the range of $0.001 - 1.0$, one can calculate the mixing time for neutron-antineutron oscillation as a function of Mass of color Higgs scalar ($B - L$ breaking scale) as shown in Fig.7 (Fig.8).

The $n - \bar{n}$ amplitude can be translated into the $n - \bar{n}$ oscillation time as,

$$\tau_{n-\bar{n}}^{-1} = \delta m_{n-\bar{n}} = C_{\text{QCD}}(\mu_{\Delta}, 1 \text{ GeV}) |A_{n-\bar{n}}^{1-\text{loop}}| \quad (31)$$

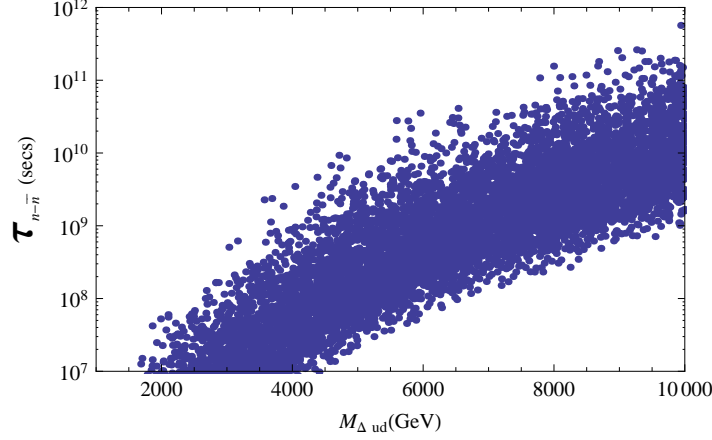


FIG. 7: Estimation of $\tau_{n-\bar{n}}$ as a function of di-quarks mass $M_{\Delta_{ud}}$.

with $C_{\text{QCD}}(\mu_{\Delta}, 1 \text{ GeV}) = 0.1 \text{ GeV}^6$ as used in ref.[9]. The estimated $n - \bar{n}$ oscillation time for various choice of model parameters i.e, $f_{ud11} \leq 10^{-5}$, $M_S = (100 - 5000) \text{ GeV}$, B-L breaking scale from (3-5)TeV and the masses of $M_{\Delta_{ud/dd}}$ between M_S and V_{B-L} , $\lambda \simeq 0.01 - 1.0$ is presented in Table.II.

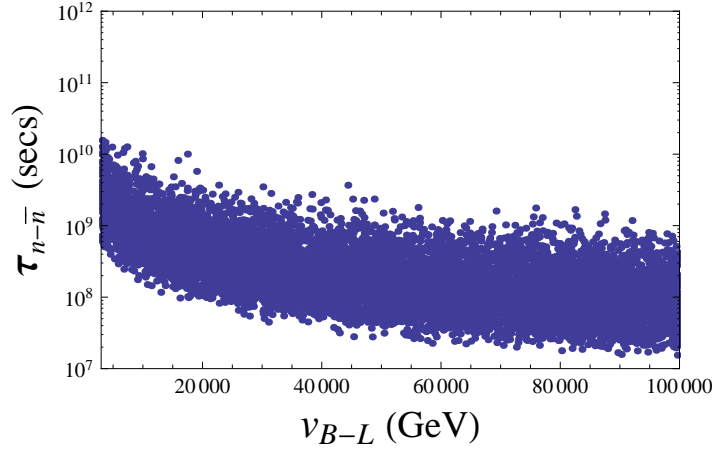


FIG. 8: Estimation of $\tau_{n-\bar{n}}$ as a function of $B - L$ breaking scale v_{B-L} while keeping other model parameters within their allowed range consistent with mechanism of post-sphaleron baryogenesis.

C. Coupling Unification including diquarks at TeV scale

It is prominent that the post-sphaleron baryogenesis and neutron-antineutron oscillation phenomena require existence of color Higgs scalars, having masses around TeV scale. In this

subsection, we intend to examine whether unification of gauge couplings is still possible after the addition of extra color scalars Δ_{ud} , Δ_{dd} , Δ_{uu} to the existing particle content as noted in Sec. III, by studying their respective renormalization group equations. The one-loop beta coefficients derived for the present model along with their gauge symmetry groups, range of mass scales and spectrum of Higgs scalars necessary for gauge coupling unification to explain TeV scale post-sphaleron baryogenesis and neutron-anti-neutron oscillation are given below

$$(i) \mu = \mathbf{M_Z}(91.817 \text{ GeV}) - \mathbf{M_T}(1 \text{ TeV}) : \quad \mathcal{G} = \mathcal{G}_{2_L 1_Y 3_C} \equiv \text{SM},$$

$$\text{Higgs: } \Phi(2, 1/2, 1)_{10} : \quad \mathbf{a_i} = (-19/6, 41/10, -7) ; \quad (32)$$

$$(ii) \mu = \mathbf{M_T}(1 \text{ TeV}) - \mathbf{M_{B-L}}(3 \text{ TeV}) : \quad \mathcal{G} = \mathcal{G}_{2_L 1_Y 3_C}$$

$$\text{Higgs: } \Phi(2, 1/2, 1)_{10} \oplus S(1, 0, 1)_{126} \subset \Delta_R \oplus \Delta_{u^c d^c}(1, -1/3, 6^*)_{126} \oplus \Delta_{d^c d^c}(1, 2/3, 6^*)_{126}$$

$$\oplus \Delta_{u^c u^c}(1, -4/3, 6^*)_{126} :$$

$$\mathbf{a_i} = (-19/6, 207/30, -27/6) \quad (33)$$

$$(iii) \mu = \mathbf{M_{B-L}}(3 \text{ TeV}) - \mathbf{M_\Omega}(10 \text{ TeV}) : \quad \mathcal{G} = \mathcal{G}_{2_L 1_R 1_{B-L} 3_C}$$

$$\text{Higgs: } \Phi_1(2, 1/2, 0, 1)_{10} \oplus \Phi_2(2, -1/2, 0, 1)_{10'} \oplus \Delta_R(1, 1, -1, 1)_{126} \oplus \chi_R(1, 1/2, -1/2, 1)_{16},$$

$$\oplus \Delta_{u^c d^c}(1, 1, -2/3, 6^*)_{126} \oplus \Delta_{d^c d^c}(1, 0, -2/3, 6^*)_{126} \oplus \Delta_{u^c u^c}(1, 0, -2/3, 6^*)_{126} :$$

$$\mathbf{a_i} = (-3, 35/4, 45/8, -27/6) \quad (34)$$

$$(iv) \mu = \mathbf{M_\Omega}(10^4 \text{ GeV}) - \mathbf{M_C}(10^5 - 10^6 \text{ GeV}) : \quad \mathcal{G} = \mathcal{G}_{2_L 2_R 1_{B-L} 3_C}$$

$$\text{Higgs: } \Phi_1(2, 2, 0, 1)_{10} \oplus \Phi_2(2, 2, 0, 1)_{10'} \oplus \Delta_R(1, 3, -1, 1)_{126} \oplus \chi_R(1, 2, -1/2, 1)_{16},$$

$$\oplus \Delta_{u^c d^c}(1, 3, -2/3, 6^*)_{126} \oplus \Delta_{d^c d^c}(1, 3, -2/3, 6^*)_{126} \oplus \Delta_{u^c u^c}(1, 3, -2/3, 6^*)_{126}$$

$$\oplus \Omega_R(1, 3, 0, 1)_{210}$$

$$\mathbf{a_i} = (-8/3, 4/3, 55/4, -2) \quad (35)$$

In analogy to the above discussion, we have two scenarios; one without bitriplet and another with bitriplet Higgs scalar (3,3,1) under the Pati-Salam group $SU(2)_L \times SU(2)_R \times SU(4)_C$ while its effect has been included from M_C onwards to the unification scale M_U . Accordingly, we have estimated the one-loop beta coefficients for these two scenarios as

$$(v) \mu = \mathbf{M_C} - \mathbf{M_\xi} : \quad \mathcal{G} = \mathcal{G}_{2_L 2_R 4_C}$$

$$\text{Higgs: } \Phi_1(2, 2, 1)_{10} \oplus \Phi_2(2, 2, 1)_{10'} \oplus \Delta_R(1, 3, \overline{10})_{126} \oplus \chi_R(1, 2, \overline{4})_{16} \oplus \Omega_R(1, 3, 15)_{210}$$

$$\mathbf{a_i} = (-8/3, 29/3, -14/3) \quad (36)$$

(vi) $\mu = \mathbf{M}_\xi - \mathbf{M}_\mathbf{P} : \mathcal{G} = \mathcal{G}_{2_L 2_R 4_C}$

$$\begin{aligned} \text{Higgs: } & \Phi_1(2, 2, 1)_{10}, \Phi_2(2, 2, 1)_{10'}, \Delta_R(1, 3, \overline{10})_{126}, \chi_R(1, 2, \overline{4})_{16}, \Omega_R(1, 3, 15)_{210} + \xi(2, 2, 15)_{126'}, \\ \mathbf{a}_i = & (7/3, 44/3, 2/3) \end{aligned} \quad (37)$$

(vii) $\mu = \mathbf{M}_\mathbf{P} - \mathbf{M}_\mathbf{U} : \mathcal{G} = \mathcal{G}_{2_L 2_R 4_C}$

$$\begin{aligned} \text{Higgs: } & \Phi_1(2, 2, 1)_{10}, \Phi_2(2, 2, 1)_{10'}, \Delta_R(1, 3, \overline{10})_{126}, \Delta_L(3, 1, 10)_{126}, \chi_R(1, 2, \overline{4})_{16}, \chi_L(1, 2, 4)_{16}, \\ & \Omega_R(1, 3, 15)_{210}, \Omega_L(3, 1, 15)_{210}, \xi(2, 2, 15)_{126'}, \Sigma'(1, 1, 15)_{210}, \\ \mathbf{a}_i = & (44/3, 44/3, 6) \end{aligned} \quad (38)$$

The gauge coupling unification after the addition of extra color sextet scalars particles is

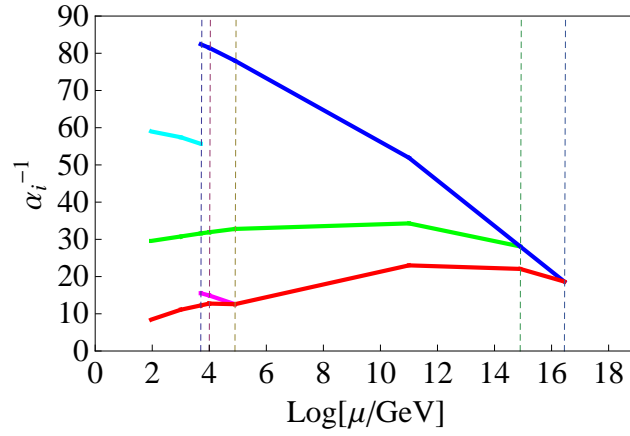


FIG. 9: Coupling unification for the present model where $\Delta_{u^c d^c}$, $\Delta_{d^c d^c}$, and $\Delta_{u^c u^c}$ have been included at TeV scale keeping in mind that these particle mediate neutron-antineutron oscillation and baryon asymmetry and including $\xi(2, 2, 15)$ around 10^{12} GeV in order to fit the fermions masses at GUT scale.

shown in Fig. 9 with the allowed mass scales desirable for our model predictions,

$$\begin{aligned} M_{B-L} &= 4 - 7 \text{ TeV}, M_\Omega = 10 \text{ TeV}, M_C = 10^5 - 10^6 \text{ GeV}, \\ M_P &\simeq 10^{14.65} \text{ GeV and } M_U \simeq 10^{16.25} \text{ GeV}. \end{aligned} \quad (39)$$

VI. VIABILITY OF THE MODEL

As already known, the lepton flavor and lepton number violating dilepton signals can be probed from the production of heavy RH Majorana neutrino via $p + p \rightarrow W_R^\pm \rightarrow \ell_\alpha^\pm + N_R$,

from which N_R can be further decayed into $N_R \rightarrow W_R^* \rightarrow \ell_\beta^\mp = 2j$. This process, being the main channel for N_R production via on-shell Z_R production and W_R fusion, needs to be verified at LHC and our model suits the purpose, since we have W_R , Z_R gauge bosons and scalar diquarks at TeV scale. A more pleasant situation is that the model, though non-supersymmetric, predicts similar branching ratios as in supersymmetric models for LFV processes like $\mu \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$, and $\tau \rightarrow e\gamma$. And the predicted branching ratios for these LFV decays, being closer to the current experimental search limits can be used to verify the left-right framework in this model. Moreover the estimated neutron-antineutron oscillation mixing time, gauge coupling unification and proton life time in the model stay in the range of ongoing search experiments.

Besides all these points, the model can also predict a number of verifiable new physical quantities like (i) new non-standard contribution to $0\nu 2\beta$ rate in the $W_L - W_L$ channel, (ii) contributions to branching ratios of lepton flavor violating (LFV) decays, (iii) leptonic CP-violation due to non-unitarity effects, (iv) experimentally verifiable proton decay modes such as $p \rightarrow e^+\pi^0$, provided the gauged inverse seesaw mechanism is found to be operative. We find it appropriate to mention here that these physical quantities were also discussed in a recent work [19], but in that model the asymmetric left-right gauge symmetry was incorporated at $\simeq 10$ TeV.

VII. CONCLUSION

We have closely studied the mechanism of post-sphaleron baryogenesis, that can potentially explain matter-antimatter asymmetry of the present universe, by analyzing the basic interactions using quarks and diquark Higgs scalars under high scale Pati-Salam symmetry and low scale SM like interactions at TeV scale. The study estimates the total baryon asymmetry to be $\eta_B \simeq \mathcal{O}(10^{-10})$ and neutron-antineutron oscillation with mixing time to be $\tau_{n-\bar{n}} \simeq \mathcal{O}(10^{-10} - 10^{-8})$ secs which can be accessible at ongoing search experiments. We have made an humble attempt to embed the framework of PSB in a non-SUSY $SO(10)$ model with Pati-Salam symmetry as a low scale intermediate breaking step where we have shown a strong interlink between post-sphaleron baryogenesis and neutron-antineutron oscillation operative at TeV scale and laid out a novel mechanism of inducing required CP-asymmetry via the SM W_L^\pm loops.

More essentially, we have embedded TeV scale LR model within the framework of $SO(10)$ model where the predicted mass for light neutrinos matches with the neutrino oscillation data. Our calculations indicate that TeV scale masses of W_R^\pm and heavy RH neutrinos can also give dominant non-standard contributions to neutrinoless double beta decay which may sound crucial to the experimentalists. Some more good features of the model are explanation of non-zero light neutrino masses via extended/inverse seesaw mechanism, new non-standard contribution to neutrinoless double beta decay, leptonic CP-violation from non-unitary effects.

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